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The effect of cattle management on soil carbon: Implications for climate change

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The Effect of Cattle Management on Soil Carbon; Implications for Climate Change

Kelly Livernoche

A thesis submitted to the Graduate Faculty of

JAMES MADISON UNIVERSITY

In

Partial Fulfillment of the Requirements

for the degree of

Master of Science

Department of Biology

August 2017

FACULTY COMMITTEE:
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Dedication

This work is dedicated to my grandmother, Mary Lou, who instilled in me the love of the Shenandoah Valley, guided me in becoming a successful student, and taught me how to make meatloaf. I love you, Nan.
Acknowledgements

I must first and foremost thank my thesis advisor, Dr. Griscom, for providing me with the opportunity to earn my Master’s degree at JMU. None of this would be possible without your support, guidance, and patience. I would also like to thank my thesis committee members, Dr. Wiggins and Dr. Eaton, for their additional support and unique contributions to my project. A special thank you is bestowed to Dr. May, whose dedication and enthusiasm to not only my research but to the entire biology graduate program is often overlooked. We are a functional and motivated group of scientists because to you. I must also thank Mr. Flint for helping me become a better instructor during these past two years and whose advice and encouragement I will carry with me throughout my career. These acknowledgments would not be complete without recognizing all of my fellow biology graduate students, both past and present. I would like to specifically acknowledge Jessie Mandirola, Romie Powell, Phoebe Cook, Jon Studio, and Matthew Harris for their continual insight, reassurance, and fun times.
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Abstract

In naturally occurring ecosystems, forests function as substantial carbon sinks, storing carbon in soil and in biomass that would otherwise exist in the atmosphere as carbon dioxide. The conversion of forested land to cattle pastures and their associated operational processes are noteworthy contributors to recent increases in global carbon emissions and subsequent climate change. However, appropriately managed cattle pastures have potential to be reservoirs for carbon. Rotational cattle pastures, where cattle are moved between enclosed sections of pasture, may improve soil carbon content compared to conventional practices. In rotational cattle pastures, a more even distribution of manure increases plant biomass, and increased cattle movement decreases soil compaction, thereby reducing erosion and loss of soil carbon. This study quantified differences in soil carbon and bulk density (soil compaction) within and between a high-frequency rotational pasture (HFR), a low-frequency rotational pasture (LFR), and a conventional non-rotational (NR) pasture. Soil samples were collected from top, middle, and bottom slope positions and were separated by soil depth (0-10, 10-20, and 20-30 cm). Bulk density was determined using dry soil weights, and soil carbon was estimated as soil organic matter (SOM) with the loss-on-ignition technique. SOM was found to be greatest in the HFR pasture (6.61 ± 0.27%), followed by the LFR (6.00 ± 0.37%), and the NR pasture (3.47 ± 0.24%; p < 0.001). Inversely, bulk density was lowest in the HFR pasture (0.79 ± 0.01 g/cm³), followed by the LFR pasture (0.86 ± 0.04 g/cm³), and the NR pasture (0.93 ± 0.02 g/cm³; p < 0.001). Slope position had no effect on bulk density and
only influenced SOM in the HFR pasture, such that SOM was greater at the top slope position (7.51 ± 0.51%) compared to the middle (6.25 ± 0.41%) and bottom (6.06 ± 0.40%) positions. Generally, SOM was greatest and bulk density lowest at 0-10 cm and SOM decreased and bulk density increased with lower soil depths. This study suggests that rotational cattle pastures could be one pathway for mitigating climate change through greater carbon sequestration and soil carbon storage.
I. Introduction

Variation in global climate is apparent on a geological timescale, but the recent temperature increase in the past several decades is overtly pronounced. Crowley (2000) suggests that about 75% of temperature increases in the twentieth century are the result of unnatural global variations. Since the Industrial Revolution, atmospheric carbon dioxide concentrations have increased from 280 ppm in 1850 to 390 ppm in 2014 (IPCC 2014). Causes of this climate change are deemed anthropogenic and include the burning of nonrenewable fossil fuels, agricultural byproducts, and deforestation.

The recent movement towards high-intensity agricultural practices, including industrialized cattle pastures, has contributed to atmospheric carbon dioxide as a result of land-use change, land degradation, and the breakdown of animal manure. Approximately 9% of anthropogenic global carbon dioxide emissions are from livestock (FAO 2006), largely a result of damaging effects on soil (Trimble & Mendel 1995).

In naturally occurring ecosystems, forests function as substantial carbon sinks, storing carbon in soil and biomass that would otherwise exist in the atmosphere as carbon dioxide (Compton & Boone 2000; Dangal et al. 2013; Lal 2005). Carbon is innately held within forest soils as soil organic matter (SOM), which is added to the soil from aboveground biomass, detritus material, and other terrestrial inputs. The removal of this continual organic carbon source following conversion to agricultural land considerably depletes its abundance in soil and noticeably results in a decline in soil quality. Conventional agricultural practices tend to rapidly deplete SOM with little to no carbon contributions (Da Silva et al. 2014; Gregorich et al. 2001). However, more sustainable methods have potential to enhance carbon stocks through carbon sequestration (Foereid...
& Hogh-Jensen 2004; Jarecki et al. 2005; Lal 2004; Leifield & Fuhrer 2010; Paustian et al. 2016), which is defined as the securement of atmospheric carbon dioxide into biotic and pedologic reserves (Lal 2007). This process is suggested to help offset greenhouse gas emissions produced from agricultural practices (Teague et al. 2016). However, even the most sustainable practices are unlikely to return agricultural soil carbon content to its natural forested state (Bobrovsky et al. 2010; Gregorich et al. 2001; Page et al. 2013).

The benefits of preserving organic matter in soils are evident, especially in agricultural lands. Substantial quantities of SOM promote an abundance of diverse soil organisms, provide nutrients to plants, and increase water-holding capacity (FAO 2005). Insufficient SOM results in a decrease of soil quality, evident by the inability of soil to perform the necessary ecological functions to support life (Lal 1997). Low levels of SOM have been shown to decrease plant abundance in both agricultural (Céspedes-León 2015; Ishaq et al. 2001) and forest settings (Lal 2005). Farm productivity, resilience, and sustainability are strengthened by adequate quantities of soil carbon (Meyer et al. 2015). Therefore, by consciously improving the sustainability of agricultural practices, they have great potential to be substantial sinks of SOM (Lal 2007), thereby limiting greenhouse gas contributions (Olson et al. 2014) while increasing both farm productivity and profitability (Rutledge et al. 2015). Additionally, improved soil carbon and soil quality may improve the ability of agricultural lands to be more resilient against changing climates (Teague et al. 2016).

The evidence supporting the benefits of sustainable crop farming to improve soil carbon is overwhelming. A meta-analysis of 74 studies by Gattinger et al. (2012) found increased SOC concentrations, carbon stocks, and sequestrations rates in organic farming
practices (including the addition of plant residue and manure as organic compost, cover crops, and reduced tillage in crop systems) compared to traditional management (but see Leifeld et al. 2013). However, implications for sustainable cattle management in temperate ecosystems are less understood.

In degraded cattle pastures, a decrease in soil carbon is often observed as a result of fewer organic matter inputs and extensively compacted soil. Overgrazing of land by cattle permits the release of carbon dioxide from soil erosion (Da Silva et al. 2014; Wu & Tiessen 2002), perpetuated by the loss of vegetation cover (Koiter et al. 2017) and limited water infiltration (Hamza & Anderson 2005). In a highly degraded and overgrazed pasture in Argentina, soil carbon was found to be significantly lower when compared to a moderately restored site (no overgrazing in the past ten years) and a highly restored site (cattle excluded for twenty years; Abril & Butcher 2001), suggesting a correlation between the presence of cattle and soil carbon content.

Rotating cattle, or moving cows at some frequency between permanent or temporary enclosures within a pasture, both improves aboveground biomass and limits soil compaction throughout the pasture (Fig. 1). Previous research suggests that this sustainable practice improves stored soil carbon and reduces soil carbon emissions. Mazzetto et al. (2015) found that compared to continuous cattle management, soil carbon emissions were significantly lower in rotational pastures. Teague et al. (2011) observed that the percentage of SOM in a North American tall grass prairie rotational pasture (0.27 ha\(^{-1}\) moved between multiple paddocks) was significantly greater than both a light continuous (0.14 cattle ha\(^{-1}\)) and a heavy continuous pasture (0.27 cattle ha\(^{-1}\)) after nine years of management. In addition, SOM in the rotational pasture was statistically similar
to that of an area in which cattle have been excluded for seven years (Teague et al. 2011). A similar study also conducted in a prairie region by Wang et al. (2015) found that soil organic carbon was 27% greater in a rotational pasture compared to one that is heavily grazed. Soil organic carbon was significantly reduced in a grazed arid region of China, but content increased with cattle exclusion (Pei et al. 2008). In the same arid ecosystem, soil carbon decreased as grazing intensity increased (Han et al. 2008). These past studies suggest that there is a correlation between grazing intensity and soil carbon content.

A relationship between soil carbon and bulk density (soil compaction) is discernable (Fig. 1). With greater soil compaction, root growth is compromised, limiting plant biomass and consequently, potential organic matter inputs. In addition, decreased root growth causes sloped surfaces to be more susceptible to soil loss through erosion. Soil organic carbon has previously been found to be negatively correlated with soil compaction in semiarid soil (Blanco-Canqui et al. 2015). A decrease in soil carbon in association with compact soils results in a greater risk of soil erosion (Adisa & Nortcliff 2011; Lado et al. 2004; Meyer et al. 2015).

Changes in bulk density have often been observed in cattle pastures, having indirect implications on SOM. With increased bulk density, or more compact soil, reductions in soil carbon content are often observed (Han et al. 2008; Pei et al. 2008). However, by actively managing cattle to prevent overgrazing, soil compaction within pastures can be controlled. After five months, Bezkorowajnyj et al. (1993) observed a significant increase in soil compaction in pastured areas with cattle compared to areas without. Bulk density is often greatest in grazed land, and the soil becomes less compact with the removal of cattle (Pei et al. 2008). Abril and Butcher (2001) found that bulk
density was greatest in overgrazed and non-rotated pastures, while soils in rotated sites were less compact. This could result from the greater distribution of cattle activity around the pasture. However, Teague et al. (2011) found that although soil carbon had been positively correlated, no significant difference in pasture soil bulk density between heavy continuous, light continuous, and rotational cattle management was observed. In addition to more evenly distributing cattle activity, rotating cattle also allows for the spreading of manure, which is also correlated to changes in physical soil properties (Dunjana et al. 2012), including bulk density (Blanco-Canqui et al. 2015). A uniform distribution of manure throughout a pasture could also be directly related to an overall decrease in bulk density (Blanco-Canqui et al. 2015).

The presence of cattle can alter additional qualities of the soil as they move about a pasture that have implications for SOM content. An adult cow (~1,000 lbs) can apply up to 1.7 kg cm\(^2\) of ground pressure on hoof-bearing area (Bezkorowajnyj et al. 1993), often resulting in negative impacts on soil structure, especially when cattle tend to congregate (Sigua & Coleman 2006). Trampling by cattle can affect physical, chemical, and microbial properties of soil (Hiltbrunner et al. 2012). This behavior also reduces vegetation cover near settlement sites (Dunne et al. 2011), root growth (Bezkorowajnyj et al. 1993) and water infiltration rates (Bezkorowajnyj et al. 1993; Blanco-Canqui et al. 2015; Hamza & Anderson 2005). A review of livestock grazing in arid ecosystems suggests that percent grass cover, total vegetation biomass, and water infiltration rate were significantly reduced compared to non-grazed lands (Jones 2000). Similarly, soil erosion was greater with the presence of cattle (Jones 2000). Pei et al. (2008) likewise found that percent grass cover was significantly greatest in an area in which cattle have
been excluded for six years, followed by two-year exclusion, and presently grazed area. These consequences on soil quality have indirect effects on SOM, further reducing its content on overgrazed and degraded pastures.

There are also inherent landscape factors that influence soil carbon and bulk density within a pasture. A study by Sigua and Coleman (2010) discovered that soil organic carbon on a rotational pasture in a tropical climate was significantly affected by slope aspect, slope position, and soil depth. Carbon content was suspected to be greatest at the top slope position followed by the middle position and the bottom position, a potential outcome of the preference of cattle to congregate downslope (Sigua & Coleman 2006). This reduces vegetation and limits the input of carbon into the soil at this slope position. Because cattle are herded animals, they tend to graze in close proximity to one another. Sigua and Coleman (2009) suggest that soil compaction is greatest near cattle congregation sites, such as near water or in shaded areas. Congregation sites can also be associated with decreased soil moisture and reduced vegetation, influencing both soil fertility (Sigua & Coleman 2006) and soil organic carbon (Franzluebbers et al. 2000). Others suggest that in eroded landscapes, the removal of topsoil could lead to the deposition of soil organic carbon downslope (Bajracharya et al. 2000; Farenhorst 2006), as opposed to reduced content due to cattle congregate suggested by Sigua and Coleman (2009). This loss of soil through erosion also affects plant growth and increases soil microbial activity through aeration (Bajracharya et al. 2000), further reducing carbon content by limiting biomass and increasing the release of carbon dioxide by soil microbes.
Figure 1. A hypothetical model of the process by which soil carbon is increased in a rotational cattle system, providing a potential pathway to mitigate climate change.

It is suspected that continual movement of cattle will improve soil carbon through three pathways (Fig. 1). First, the rotation of cattle will increase the distribution of manure, which will in turn improve overall aboveground biomass within the pasture. This provides more organic matter inputs that can be returned to the soil. Second, the rotation of cattle should decrease bulk density. This reduction in soil compaction will reduce soil loss through erosion, improve root growth, and increase water infiltration. Together, this
will result in less carbon loss down a sloped surface. Finally, rotating cattle will reduce overgrazing and its negative consequences on plant biomass and soil loss.

The purpose of this study was to quantify the effect of cattle rotational frequency on soil carbon by both direct (SOM) and indirect (bulk density) measures. Three cattle pastures that implement different methods of managing cattle were used for this study, ranging from conventional, non-rotational methods to intensive, rotational management. It was predicted that (1) SOM would be greatest and bulk density lowest (improved soil health) in pastures of rotated cattle and (2) SOM and bulk density would vary with respect to topography only in non-rotated pasture, with SOM lowest and bulk density highest at bottom slope positions.

II. Methods

Study Sites

Three cattle pastures in Swoope, Augusta County, Virginia that implement different cattle management strategies (non-rotational versus rotational) were selected for this study (Table 1; Fig. 2). The climate in this region is temperate with an average annual temperature of 13°C and average annual precipitation of about 1100 mm. A combination of limestone, sandstone, and shale underlay the pastures. All soils are typic paleudults or typic hapludults, but unique soil series differ between sites (NRCS 2016). Land in this area has been used for cattle grazing for at least two hundred years. Each pasture features a landscape of rolling hills and is associated with forested land on the property adjacent to grazed land. All farms graze Angus cattle on grass within the pasture when not covered with snow, and cattle are fed straw when grass is not accessible. The
densities of cattle differ between sites (Table 1). However, it is not believed that such differences would influence the conclusions of this study. On the pastured land, no chemical fertilizers, pesticides, herbicides, or insecticides are applied. Samples were collected in the summer of 2016.

Table 1. Geologic, management practices, and landscape factors of three cattle pastures in Swoope, Augusta County, Virginia.

<table>
<thead>
<tr>
<th></th>
<th>Non-rotational Pasture (NR)</th>
<th>Low-frequency Rotational Pasture (LFR)</th>
<th>High-frequency Rotational Pasture (HFR)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bedrock</strong></td>
<td>Limestone, Sandstone, Shale</td>
<td>Limestone, Sandstone, Shale</td>
<td>Limestone, Sandstone, Shale</td>
</tr>
<tr>
<td><strong>Soil Series</strong></td>
<td>Frederick, Christian</td>
<td>Frederick</td>
<td>Edom, Chilhowie</td>
</tr>
<tr>
<td><strong>History</strong></td>
<td>200+ years grazing</td>
<td>200+ years grazing</td>
<td>200+ years grazing</td>
</tr>
<tr>
<td><strong>Current Management</strong></td>
<td>In current family since 1972</td>
<td>Rotational since 2003</td>
<td>Rotational since 1964</td>
</tr>
<tr>
<td><strong>Total Size of Pasture (ha)</strong></td>
<td>61</td>
<td>200</td>
<td>97</td>
</tr>
<tr>
<td><strong>Type of Cattle</strong></td>
<td>Angus</td>
<td>Angus</td>
<td>Angus, lower quantities of Piedmontese and Simmental</td>
</tr>
<tr>
<td><strong>Number of Cattle</strong></td>
<td>~100</td>
<td>~145</td>
<td>~125</td>
</tr>
<tr>
<td><strong>Density of Cattle</strong></td>
<td>1.64</td>
<td>0.72</td>
<td>1.29</td>
</tr>
<tr>
<td><strong>Enclosure Size (ha)</strong></td>
<td>No enclosures</td>
<td>~4</td>
<td>~0.6</td>
</tr>
<tr>
<td><strong>Duration in Enclosures</strong></td>
<td>-</td>
<td>~10</td>
<td>~1</td>
</tr>
<tr>
<td><strong>Sample Area (ha)</strong></td>
<td>1</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td><strong>Slope Aspect</strong></td>
<td>Northeast</td>
<td>Northwest</td>
<td>Northwest</td>
</tr>
<tr>
<td><strong>Slope Inclination (%)</strong></td>
<td>14</td>
<td>21</td>
<td>9</td>
</tr>
</tbody>
</table>
The non-rotational (NR) pasture (38°7’ N, 79°11’ W) features Frederick and Christian soils. The property has been owned by its current family since 1972. They have approximately 100 cattle in 61 ha (1.64 cattle ha$^{-1}$). Cattle are not intentionally rotated between enclosures and have access to the entire extent of the pasture. The area studied within this pasture encompass approximately 1 ha with a northeast-facing slope of ~14% inclination.

The low-frequency rotational (LFR) pasture (38°8’ N, 79°12 W) is underlain by Frederick soil. The owners began rotating cattle in 2003 between about 10 ha permanent enclosures among 200 total ha. They own approximately 145 cattle (0.72 cattle ha$^{-1}$) that are rotated every 1-3 days, spending on average 10 days per year in each enclosure. The area sampled consisted of approximately 0.8 ha on a northwestern slope aspect of ~21%.

Figure 2. Locations of three cattle pastures implementing different management strategies in Swoope, Augusta County, Virginia.
The high-frequency rotational (HFR) pasture (38°6’ N, 79°13’ W) features Edom and Chilhowie soils. The pasture has implemented the current rotational management since 1964. The owners graze about 125 cattle on 97 ha (1.29 cattle ha\(^{-1}\)). Cattle are rotated daily between 0.6 ha portable enclosures of electric fencing, spending about 1 day per year in any particular area of pasture. According to the owner of the pasture, the “crowding [of cattle within the enclosures] creates more aggressive hoof action to chip up their manure, treading it into the ground to stimulate fertility [and] shades their urine so it seeps into the ground rather than evaporating” (Salatin 2012). The area sampled was approximately 1 ha on a northwestern-facing slope of ~10%. In addition to Angus cattle, this pasture also occasionally grazes other breeds in lower quantities, including Piedmontese and Simmental.

**Soil Sample Collection**

Soil samples were collected from each pasture and forest using a regular (4 inch) soil auger. Prior to augering, the aboveground biomass was removed at the collection site.

At the NR and HFR pastures, a 100 m transect was established along a ridgeline. Every 20 m, a perpendicular 110 m transect was extended down the sloped land, equaling 6 total transects (Fig. 3). Along these transects, a soil sample at each depth (0-10, 10-20, 20-30 cm) was taken every 10 m. Sampling design had to be slightly modified at the LFR pasture due to space constrains (2 transects of 70 m and 1 transect of 60 m). This sampling design resulted in 72 soil samples per cattle treatment for each slope position and soil depth for the NR and HFR pastures and 18 samples per treatment for each slope position and soil depth for the LFR pasture.
Figure 3. Experimental design implemented at three cattle pastures (non-rotational (NR), low-frequency rotational (LFR), and high-frequency rotational (HFR) in Swoope, Augusta County, Virginia. A transect was established along a ridgeline, and perpendicular transects were established 20 m apart down the length of the slope. The number of transects was dependent on the available space at each pasture. Every 10 m, 3 soil samples were collected with a regular (4”) soil auger, one at each depth of 0-10, 10-20, and 20-30 cm. Soil was categorized as top, middle, or bottom slope in accordance with its relative location along the sloped surface. For each slope position and soil depth, a total of 72, 18, and 72 samples for NR, LFR, and HFR pastures, respectively. A similar design was used in an adjacent forest site on each pasture.

An adjacent forested area of land was sampled at each pasture site. One or more transects were run at each forest, the number and length depending on the space available. This resulted in 48, 18, and 15 samples for the NR, LFR, and HFR forest sites, respectively.
**Preparation of Soil Samples**

All soil samples were dried at 105°C for 24 hours. Samples remained at this temperature for analysis.

**Calculation of Bulk Density**

Dried soil samples were weighed. The volume of the soil auger used for an individual collection at each soil depth was calculated to be 502.65 cm\(^3\). Bulk density (g cm\(^{-3}\)) was determined using the following equation:

\[
\text{bulk density} = \frac{\text{dry soil weight (g)}}{\text{volume of container (cm}^3\text{)}}
\]

**Estimation of SOM Content**

Soil organic matter (SOM) was estimated using the loss-on-ignition technique (LOI; Combs & Nathan 1998). Approximately 5 g of oven-dried (105°C) soil was heated in a muffle furnace at 360°C for 2 hours. Once cooled to < 150°C, the soil was re-weighed. The percent weight loss-on-ignition was calculated using the following equation:

\[
\text{LOI} = \frac{\text{wt. at 105°C} - \text{wt. at 360°C}}{\text{wt. at 105°C}} \times 100
\]

**Grain Size Analysis**

The hydrometer method of grain size analysis protocol was adapted from procedures by the NRCS (2014). To 350 mL of deionized (DI) water and 10 mL of 5% solution of sodium hexametaphosphate, 40 g of -10 sieved dried soil were added. The
mixture was agitated with a blender for 4 min and was poured into a nest of sieves and a bottom pan (No. 40 to retain coarse-to-medium sand and No. 230 to retain fine and very fine sand). All remaining sediment was removed with DI water from the container. The solution was thoroughly rinsed through the sieves. Grains retained in the sieves were dried for 24 hours at 105°C. The subsequent dry weight constituted the sand fraction of the soil sample.

The solution remaining in the bottom pan was transferred to a 1000 mL graduated cylinder. The remaining volume of the graduated cylinder was filled to 1000 mL with DI water. The solution was mixed for 40 sec with a stir rod. The weight of the solution was determined using a hydrometer, which represented the silt and clay fraction of the sample. The solution was left undisturbed for 2 hours, and another hydrometer reading was taken. After this time, the silt fraction had presumably settled below the reach of the hydrometer. Therefore, the second hydrometer reading recorded just the weight of the clay fraction. The weight of the silt fraction was determined by subtracting the second hydrometer reading from the first reading. The percentages of sand, silt, and clay were calculated by dividing the weight of each fraction by the total recovered weight (as opposed to the initial weight) to normalize the data.

This procedure was performed on a subsample of the soil samples. From each transect at each pasture, a random representative sample was selected from top, middle, and bottom slope position, only at the 0-10 cm soil depth.
Statistical Analysis

In order to ensure individual soil samples were independent from one another, SOM and bulk density measurements were averaged together for top, middle, and bottom slope positions in each transect. For example, the four soil samples at the top-most part of the slope (each 10 m apart) were averaged to produce one sample representing the top slope position at that transect, while still keeping soil depths separate (Fig. 3). SOM and percent clay were square root transformed to improve the normality of the data. All subsequent analyses were performed in RStudio (version 0.99.903) with these averages and transformations.

Two three-way analyses of variance (ANOVA) were performed to test the effect of pasture management type, slope position, soil depth and all interactions on both SOM and bulk density. There was no effect of the three-way interaction of pasture*position*depth on SOM and bulk density, so this interaction was removed for all future analyses. Tukey’s post-hoc tests were performed with interactions to determine the differences among different pastures (NR, LFR, HFR), slope positions (top, middle, bottom), and soil depth (0-10, 10-20, 20-30 cm). Independent samples t-test were performed to determine differences of SOM and bulk density between each pasture and its adjacent forest.

Linear regression analyses were used to see if there was a relationship between bulk density and SOM for all soil samples and for each pasture individually. Similarly, the relationships between SOM and sand, silt, and clay were determined.
III. Results

Effect of Cattle Management Strategy on SOM and Bulk Density

Soil organic matter (SOM) differed between the three cattle pastures of different management strategies ($F_{2,116} = 221.82$, $p < 0.001$; Table 2). Specifically, SOM was greatest in the high-frequency rotational pasture (HFR; $6.61 \pm 0.27\%$), followed by the low-frequency rotational pasture (LFR; $6.00\% \pm 0.37\%$), and the non-rotational pasture (NR; $3.47 \pm 0.24\%$; Fig. 4a). There was also an effect of management strategy on bulk density ($F_{2,116} = 39.05$, $p < 0.001$; Table 2). Bulk density was lowest in the HFR pasture ($0.79 \pm 0.01$ g/cm$^3$), followed by the LFR pasture ($0.86 \pm 0.04$ g/cm$^3$), and the NR pasture ($0.93 \pm 0.02$ g/cm$^3$; Fig. 4b).

Table 2. Statistical results of two three-way analyses of variance (ANOVA) that tested the effect of pasture management type (non-rotational, low-frequency rotational, high-frequency rotational), slope position (top, middle, bottom), and soil depth (0-10, 10-20, 20-30 cm) on soil organic matter (SOM) and bulk density. SOM values were square root transformed. Interactions of pasture:position:depth on SOM and bulk density were not significant and were excluded for analysis. Significance ($p < 0.05$) is denoted by an asterisk.

<table>
<thead>
<tr>
<th></th>
<th>Soil Organic Matter (SOM)</th>
<th>Bulk Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>p</td>
</tr>
<tr>
<td>Pasture</td>
<td>211.82</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Slope Position</td>
<td>7.77</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Soil Depth</td>
<td>228.33</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Pasture:Position</td>
<td>5.05</td>
<td>0.001*</td>
</tr>
<tr>
<td>Pasture:Depth</td>
<td>3.64</td>
<td>0.008*</td>
</tr>
<tr>
<td>Position:Depth</td>
<td>0.26</td>
<td>0.90</td>
</tr>
</tbody>
</table>
Figure 4. Comparisons of (a) soil organic matter (SOM) and (b) bulk density between a non-rotational (NR), low-frequency rotational (LFR), and high-frequency rotational (HFR) pasture and their adjacent forests. Values of SOM and bulk density include all slope positions (top, middle, bottom) and soil depth (0-10, 10-20, 20-30 cm). SOM values were square root transformed for analysis. Capital letters denote significant differences among management types, and lowercase letters denote differences between pasture and forest within the same management type (p < 0.05).

Comparisons of SOM and Bulk Density between Pasture and Forest

The three forest sites adjacent to the pastures did not differ by SOM (F2,78 = 0.03, p = 0.96), but did differ by bulk density (F2,78 = 3.78, p = 0.027). Bulk density was greater in the NR forest than the HFR forest (p = 0.042), but no differences were observed between the NR and LFR forests or the LFR and HFR forests.

Overall pasture SOM was similar to that of the adjacent forest sites in both the LFR (6.00% ± 0.37% versus 6.70 ± 0.57%) and HFR pastures (6.65 ± 0.27% versus 7.27 ± 1.23%; Fig. 4a). Pasture SOM was significantly lower in the NR pasture (3.47 ± 0.24%) compared to that of its adjacent forest (7.78 ± 0.91%; t = 5.05, p < 0.001; Fig.
4a). Bulk density did not differ between any of the pastures and their adjacent forests (Fig 4b).

**Influence of Inherent Landscape Factors on SOM and Bulk Density**

There was a significant overall effect of slope position on SOM ($F_{2,116} = 7.77$, $p < 0.001$; Table 2). SOM was similar among all slopes positions in the NR and LFR pastures (Table 3; Fig. 5a). In the HFR pasture, SOM was greater at the top slope position compared to the middle and bottom positions (Table 3; Fig. 5a).

Table 3. Reported p-values of Tukey’s post-hoc test that examined the differences among slope positions (top, middle, and bottom) in a non-rotational (NR), low-frequency rotational (LFR), and high-frequency rotational (HFR) pasture. SOM values were square root transformed. Significance ($p < 0.05$) is denoted by an asterisk.

<table>
<thead>
<tr>
<th></th>
<th>Soil Organic Matter (SOM)</th>
<th>Bulk Density</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NR</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top-middle</td>
<td>0.51</td>
<td>0.99</td>
</tr>
<tr>
<td>Top-bottom</td>
<td>0.99</td>
<td>0.97</td>
</tr>
<tr>
<td>Middle-bottom</td>
<td>0.54</td>
<td>0.99</td>
</tr>
<tr>
<td><strong>LFR</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top-middle</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Top-bottom</td>
<td>0.27</td>
<td>0.87</td>
</tr>
<tr>
<td>Middle-bottom</td>
<td>0.33</td>
<td>0.99</td>
</tr>
<tr>
<td><strong>HFR</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top-middle</td>
<td>0.007*</td>
<td>0.99</td>
</tr>
<tr>
<td>Top-bottom</td>
<td>&lt; 0.001*</td>
<td>0.95</td>
</tr>
<tr>
<td>Middle-bottom</td>
<td>0.99</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Figure 5. Comparisons of (a) soil organic matter (SOM) by slope position, (b) SOM by soil depth, (c) bulk density by slope position, and (d) bulk density by soil depth between a non-rotational (NR), low-frequency rotational (LFR), and high-frequency rotational (HFR) pasture. Position refers to location on the sloped surface (top, middle, bottom), and soil depth refers to deepness below the soil surface (0-10, 10-20, 20-30 cm). SOM values were square root transformed for analysis. Capital letters denote differences in slope position or soil depth within the same management type (p < 0.05).
A significant effect of soil depth on SOM was also observed ($F_{2,116} = 228.33$, $p < 0.001$; Table 2). In all pastures, SOM was greatest at the depth of 0-10 cm, followed by 10-20 cm, and 20-30 cm, with one exception (Table 4; Fig. 5b). In the LFR pasture, there was no difference in SOM content between soil depths of 10-20 and 20-30 cm, but the general trend was consistent with the other pastures.

Table 4. Reported p-values of Tukey’s post-hoc test that examined the differences among soil depth (0-10, 10-20, and 20-30 cm) in a non-rotational (NR), low-frequency rotational (LFR), and high-frequency rotational (HFR) pasture. SOM values were square root transformed. Significance ($p < 0.05$) is denoted by an asterisk.

<table>
<thead>
<tr>
<th>Soil Organic Matter (SOM)</th>
<th>Bulk Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>0-10 – 10-20 cm</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>0-10 – 20-30 cm</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>10-20 – 20-30 cm</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>LFR</td>
<td></td>
</tr>
<tr>
<td>0-10 – 10-20 cm</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>0-10 – 20-30 cm</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>10-20 – 20-30 cm</td>
<td>0.06</td>
</tr>
<tr>
<td>HFR</td>
<td></td>
</tr>
<tr>
<td>0-10 – 10-20 cm</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>0-10 – 20-30 cm</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>10-20 – 20-30 cm</td>
<td>&lt; 0.001*</td>
</tr>
</tbody>
</table>

Bulk density was not significantly affected by slope position in any pasture (Table 2; Fig. 5c). However, there was an effect of soil depth ($F_{2,116} = 21.68$, $p < 0.001$; Table 2). In the NR pasture, bulk density was lower at the depth of 0-10 cm compared to 10-20 and 20-30 cm, and in the LFR pasture, bulk density was lower only at 0-10 cm compared to 20-30 cm (Table 4; Fig. 5d). No trend was observed in the HFR pasture.

The three-way interaction of pasture:position:depth was not significant for SOM or bulk density, so it was removed for all analyses. Interaction of pasture:position was
observed for SOM ($F_{4,116} = 5.05, p = 0.001$; Fig. 6a), and interaction of pasture:depth was found for both SOM ($F_{4,116} = 3.64, p = 0.008$; Fig. 6b) and bulk density ($F_{4,116} = 4.93, p = 0.001$; Table 2; Fig. 6c). All other interactions were not significant.

Figure 6. The interactions of pasture and (a) slope position on soil organic matter (SOM), (b) soil depth on SOM, (c) slope position on bulk density, and (d) soil depth on bulk density. Pasture management types include non-rotational (NR), low-frequency rotational (LFR), and high-frequency rotational (HFR) pastures. Slope position refers to location on the sloped surface (top, middle, bottom), and soil depth refers to deepness below the soil surface (0-10, 10-20, 20-30 cm). SOM values were square root transformed for analysis.
**Relationship between SOM and Bulk Density**

Considering all soil samples among the three pastures, there was a negative relationship between bulk density and SOM ($p < 0.001, R^2 = 0.524$; Fig. 7). Analyzing each pasture separately, the relationships remained significant (NR: $p < 0.001; R^2 = 0.661$; LFR: $p = 0.044, R^2 = 0.153$; NR: $p = 0.025, R^2 = 0.093$).

![Figure 7. Relationship between soil organic matter (SOM; %) and bulk density (g/cm$^3$) among a non-rotational (NR), low-frequency rotational (LFR), and high-frequency rotational (HFR) pasture. Values of SOM and bulk density include all slope positions (top, middle, bottom) and soil depths (0-10, 10-20, 20-30 cm). A significant relationship between SOM and bulk density was observed for all points ($p < 0.001, R^2 = 0.424$) and for the NR ($p < 0.001, R^2 = 0.661$), LFR ($p = 0.044, R^2 = 0.153$), and HFR ($p = 0.025, R^2 = 0.093$) pastures individually.](image-url)
Grain Size Analysis

From the subset of samples analyzed for soil texture at the soil depth of 0-10 cm at each slope position, soil textures were determined to be a loam for the NR pasture and silty clay loam for the LFR and HFR pastures (Table 5; Fig. 8). Only this soil depth was analyzed as any changes in soil properties occur most predominately near the surface (Chen et al. 2012; Lal 1996). Determination of soil texture at lower soil depths was not in the scope of this study.

Table 5. Average soil textures for all slope positions (top, middle, bottom) at a soil depth of 0-10 cm in a non-rotational (NR), low-frequency rotational (LFR), and high-frequency rotational (HFR) pasture. Percentages of sand, silt, and clay were determined using the hydrometer method of grain size analysis.

<table>
<thead>
<tr>
<th>Pasture</th>
<th>% Sand</th>
<th>% Silt</th>
<th>% Clay</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR</td>
<td>44</td>
<td>45</td>
<td>11</td>
<td>loam</td>
</tr>
<tr>
<td>LFR</td>
<td>16</td>
<td>54</td>
<td>30</td>
<td>silty clay loam</td>
</tr>
<tr>
<td>HFR</td>
<td>21</td>
<td>49</td>
<td>30</td>
<td>silty clay loam</td>
</tr>
</tbody>
</table>
Figure 8. Percentages of sand, silt, and clay for all slope positions (top, middle, bottom) at a soil depth of 0-10 cm in a non-rotational (NR), low-frequency rotational (LFR), and high-frequency rotational (HFR) pasture. Data were determined using the hydrometer method of grain size analysis.

There was a significant effect of pasture management type ($F_{2,36} = 172.75, p < 0.001$) and slope position ($F_{2,36} = 10.39, p < 0.001$) on percent clay. The interaction of pasture and position was not significant. Clay content was significantly lower in the NR pasture compared to the LFR ($p < 0.001$) and the HFR ($p < 0.001$) pastures, but no differences were found between the LFR and HFR pastures (Fig. 9). Percent clay was consistent among all slope positions except in the HFR pasture ($p < 0.001$).

Comparisons of percent sand and percent silt by pasture management type and slope position are not reported, as they are not relevant to the current study.
Figure 9. Comparison of percent clay between a non-rotational (NR), low-frequency rotational (LFR), and high-frequency rotational (HFR) pasture. Values of clay are differentiated by slope position (top, middle, bottom) and include only the soil depth of 0-10 cm. Clay values were square root transformed for analysis. Capital letters denote significant differences among management types, and lowercase letters denote differences by slope position within the same management type (p < 0.05).

Relationship between SOM and Grain Sizes

Using the subset of soil samples whose textures were determined and their respective measures of SOM, relationships between SOM and percent sand, silt, and clay
were performed. Of particular interest was the correlation between SOM and clay, as a positive relationship was anticipated (see Koiter et al. 2017).

Compiling data from all pastures, a significant positive relationship was observed between SOM and clay ($p < 0.001, R^2 = 0.510$; Fig. 10). The same trend was found for the HFR pasture ($p = 0.030, R^2 = 0.261$) but was not apparent for the NR or the LFR pastures individually.

Figure 10. Relationship between percent soil organic matter (SOM) and percent clay among a non-rotational (NR), low-frequency rotational (LFR), and high-frequency rotational (HFR) pasture. Values of clay and SOM include all slope positions (top, middle, bottom) and soil depth of 0-10 cm. A significant positive relationship between percent clay and percent SOM was observed for all points ($p < 0.001, R^2 = 0.510$) and for the HFR pasture (dashed line; $p = 0.030, R^2 = 0.261$) individually. A significant trend was not found in the NR pasture ($p = 0.72, R^2 = 0.008$) or LFR pasture ($p = 0.18, R^2 = 0.237$).
A negative relationship was found between SOM and sand for all samples (p < 0.001, $R^2 = 0.460$) and for the HFR pasture individually (p = 0.026, $R^2 = 0.275$). No relationship was observed for the NR or the LFR pastures. There was also an overall positive relationship between SOM and silt ($p = 0.035, R^2 = 0.099$), but no relationship within the individual pastures.

IV. Discussion

Effect of Cattle Management on SOM

The potential of rotational cattle management systems to sequester more carbon than traditional pastures is high. Compared to continuously grazed pastures, an increase in soil carbon has been observed in tropical (Abril & Butcher 2001; Mazzetto et al. 2015), prairie (Teague et al. 2011; Wang et al. 2015), and arid regions (Chen et al. 2012; Han et al. 2008; Pei et al. 2008), but the effects in temperate forest ecosystems are unknown. This study suggests that more frequent rotations of cattle between enclosures increase the content of soil organic matter (SOM) by 90% compared to a non-rotational system. The high-frequency rotational pasture (HFR) had significantly more SOM compared to the low-frequency rotational pasture (LFR), which has significantly more SOM than the non-rotational pasture (NR; Fig. 4a), revealing a directional relationship between rotation frequency and SOM. However, it should be noted that the LFR pasture has only been rotational for 14 years (compared to the 53 years of rotation at the HFR pasture). Therefore, SOM may continue to increase and bulk density decrease within the LFR pasture over time.
In the HFR pasture, cattle spend approximately one day per year in any one area (~0.6 ha) of the pasture. This continual movement of cattle prevents congregating and thus overgrazing. The loss of vegetation cover from overgrazing increases carbon dioxide emissions from soil erosion (Da Silva et al. 2014; Koiter et al. 2017; Wu & Tiessen 2002). In addition, continual grazing reduces the aboveground biomass that returns to the soil, some of which is stored as SOM (Chen et al. 2012).

Worldwide, forests average up to 92% more soil carbon than pasture systems in temperate regions (Chan et al. 2011; Condron et al. 2014; Dar & Sundarapandian 2013; Hoover 2011; Richardson & Stolt 2012). SOM was compared between pasture and adjacent forest in each site to determine this difference. The NR pasture had significantly less carbon than adjacent forest by 55% (Fig. 4a). On the other hand, rotational pastures had similar SOM content as adjacent forests. This would suggest that by rotating cattle in some frequency, SOM content could be comparable to that of forested land.

**Effect of Cattle Management on Bulk Density**

Trampling by cattle has deleterious effects to physical properties of the soil, which in turn influence SOM. Bulk density affects the ability of water to permeate into the soil, reducing water infiltration. However, this may vary with soil type. In a temperate grazed region in Finland, a trampled area of sandy loam soil experienced 20% water infiltration of that to a non-trampled area of the same soil, while a high-clay soil experienced only 10-15% of non-trampled areas (Pietola et al. 2005), suggesting that clayey soils suffer a greater risk of inadequate water infiltration, further limiting SOM content.
Bulk density has indirect effects on SOM. With more compact soil, there is inhibited root growth, which provides fewer organic matter inputs back into the soil. Percent vegetation cover improves with less intense trampling by cattle (Bezkorowajnyj et al. 1993; Dunne et al. 2011). Compact soils are also at greater risk of soil erosion, further resulting in a decrease in soil carbon (Adisa & Nortcliff 2011; Lado et al. 2004; Meyer et al. 2015). A negative relationship was observed between SOM and bulk density (Fig. 7). This trend was expected, as more compact soils impede root growth, decrease water infiltration, and make a surface more susceptible to carbon loss through erosion (Fig. 1). This trend has been previously observed as well (Blacno-Canqui et al. 2015; Han et al. 2008; Pei et al. 2008).

Rotating cattle may help to reduce soil compaction often generated by continuously grazed cattle. Previous research has suggested that compared to overgrazed areas, bulk density is reduced by approximately 20% when cattle are sustainably managed or excluded (Abril and Butcher 2001; Pei et al. 2008). However, this trend is not consistently observed (Jones 2000; Teague et al. 2011).

In this study, the NR pasture had the greatest values of bulk density, followed by the LFR pasture and the HFR pasture (Fig. 4b), indicating a directional relationship between rotational frequency and bulk density. The more cattle are moved about a pasture, the less time they can spend in any one area. This helps to limit soil compaction particularly in areas prone to congregation and more evenly distributes trampling of the land.

None of the sites showed differences in bulk density between pasture and adjacent forest (Fig. 4b). Because SOM in the NR pasture was significantly reduced compared to
its adjacent forest, it would be reasonable to assume that a difference in bulk density would also be observed due to their inverse relationship. Martinez and Zinck (2004) also found that soils were less compact in forest compared to pasture, and pastures became more compact with increasing age. While cattle are compacting the soil more intensely in the NR pasture compared to the rotational pastures, the effect may not be large enough to observe differences between pasture and forest. Cattle had been permitted to enter the forest from the NR pasture for at least forty years, but have been permanently excluded since the fall of 2016. This presence in the forest may have increased bulk density so that it is similar to that of the pasture.

According to the NRCS (2008), an ideal bulk density for plant growth for silty soils would be less than 1.40 g/cm³, and growth would be restricted at 1.65 g/cm³. Average bulk density values were 0.96, 0.86, and 0.79 g/cm³ for the NR, LFR, and HFR pastures, respectively. Even the most compact soils within these sites were well below the bulk density value that would limit plant growth. However, in pastures with a greater number of cattle, with less available space, or with different soil qualities, soil compaction may become an issue that will have further implications on plant growth. For example, in an arid region with coarse-textured soils, Pei et al. (2008) found that bulk density was greatest in a grazed area (1.58 g/cm³) compared to areas in which cattle have been excluded. The NRCS (2008) suggests that for sandy soils, an ideal bulk density for plant growth should be < 1.60 g/cm³. Pei et al. (2008) also found that percent ground cover of plants, plant height, and total dry weight was significantly reduced in the grazed area compared to non-grazed. The decrease in plant growth may be the result of both highly compacted soil and overgrazing by cattle.
Discrepancies in the literature on the effect of cattle on bulk density may be due to the location of study. A review of grazing in arid ecosystems found no difference in bulk density between grazed and non-grazed regions (Jones 2000). Soils in these areas are presumably high in sand content, which are less prone to compaction than those with greater proportions of clay or silt (Raghavan et al. 1977). Martinez and Zinck (2004) found that bulk density at 5-10 cm increased 42% in fine-textured soils, but only 30% in coarse-textured. However, Teague et al. (2011) found no differences in bulk density with different cattle management systems in clay-loam soils, similar to the soil textures of the current study. The density of cattle for Teague et al. (2011) was approximately 0.27 cattle ha\(^{-1}\), lower than that of the three pastures in the current study (Table 1). Therefore, both the soil texture and number of cattle influence soil compaction.

**Effect of Slope Position on SOM and Bulk Density**

It had been previously suggested that when cattle are not rotated, they may congregate in areas downslope, as conditions are often more favorable or water resources are present (Senft et al. 1985; Sigua & Coleman 2006, 2009, 2010). Sigua and Coleman (2009) found that soil compaction was greatest closer to cattle congregation sites and decreased further from the site. The disproportionate presence of cattle would decrease the availability of aboveground biomass due to overgrazing, limiting organic matter inputs. It was therefore expected that in the NR pasture, SOM would be lowest and bulk density highest at the bottom slope position. However, no differences were found with slope position in the NR pasture. Cattle may not congregate enough to have negative impacts on soil properties when provided sufficient space within a pasture. Only the HFR pasture
showed the expected trend on higher SOM at the top slope position. This may be due less to cattle congregating at the bottom and more to proximity of the upper slope forest fragments and moderate slope inclination (Tsui et al. 2004).

**Effect of Soil Depth on SOM and Bulk Density**

SOM is expected to decrease and bulk density to increase with increasing soil depth. Surface soil comprises greater root biomass and receives the immediate turnover of decomposing plant tissues and cattle manure amendments. As depth increases, soils experience greater weight and therefore become more compact compared to surface soil that is regularly disturbed. At these study sites, SOM decreased (Fig. 5b) and bulk density increased from 0-10 to 20-30 cm deep in the NR and LFR pastures. Soil at the surface will likely always be less compact, as it experiences the greatest risk to both biological and anthropogenic disturbance. Similar trends have previously been observed for both soil carbon (Sigua & Coleman 2010) and bulk density (Bezkorowajnyj et al. 1993).

Interestingly, bulk density did not change with soil depth in the HFR pasture (Fig. 5d). This pasture also featured the least soil compaction overall compared to the other pastures (Fig. 4b). Because cattle are rotated daily, a single area of the pasture experiences trampling by cattle only about one day per year. As a result, even deeper soil layers are not experiencing compaction that is present elsewhere. The deepest soil depth measured at the HFR pasture (20-30 cm) was less compact (0.77 ± 0.02 g/cm³) than the topmost depth (0-10 cm) at the NR pasture (0.83 ± 0.02 g/cm³). By rotating cattle, cows are not permitted to congregate. Every area of the pasture is subject to equal but less intense trampling, reducing bulk density and its associated consequences.
**Relationships between Cattle Management, SOM, and Clay**

Cattle management may affect the proportion of clay within a pasture. Chen et al. (2012) and Pei et al. (2008) found that clay content was greater in areas of cattle exclusion compared to continuous livestock grazing. Although larger grains are typically lost first in eroded landscapes, clay particles lose their cohesive properties when soil moisture is insufficient (Dafalla 2013), which is a consequence of soil compaction (Hamza & Anderson 2005). Therefore, in overgrazed pastures with greater bulk density and reduced vegetation, wind erosion may result in “soil coarsening” as a consequence of the loss of fine soil fractions (Pei et al. 2008). Soil texture also differed among the three cattle pastures of the current study. Specifically, clay was significantly lower in the NR pasture compared to the LFR and HFR pastures (Fig. 9). In the NR pasture, water infiltration may be limited by the increased soil compaction, presumably resulting in the loss of clay by wind or rain erosion. In addition, bacteria become essentially inactive when soils are dry (Wang & Or 2010), reducing the rate of organic matter turnover into the soil (Gougoulias et al. 2014; Negassa et al. 2015; Schimel & Schaeffer 2012).

In an attempt to determine if the decrease in SOM in the NR pasture was caused by the implemented pasture management strategy or percent clay, soil in the adjacent forest to the NR pasture was analyzed for grain size. It was found that while SOM was significantly greater in the NR forest compared to the pasture, there was no difference with respect to clay (Fig. 11). Therefore, the decrease in SOM in the NR pasture is likely the result of management type. However, Leifeld and Kögel-Knabner (2005) suggest that SOM is influenced by both soil texture and land use.
Because of this association between cattle management and clay, a positive relationship between SOM and clay was found in this study (Fig. 10) and has also been previously observed elsewhere (Koiter et al. 2017). Clay-rich soils tend to store the most soil carbon (Azlan et al. 2012; Hassink et al. 1993) due in part to the ability of clay particles to maintain soil moisture (Koiter et al. 2017) and form close associations with organic material (Sorensen 1972) that prevent rapid breakdown of SOM into carbon dioxide as a byproduct of bacterial respiration.

**Future Directions**

It has been suggested that the presence of non-native grasses has negative consequences on soil carbon pools (Liao et al. 2008) due to differences in lifecycles (Koteen et al. 2011) and plant microbial communities (Peltzer et al. 2010; Strickland et al. 2010). Preliminary data suggest that there are no differences in pasture, forest, and native grass pasture SOM or bulk density after seven years of non-native grass removal (Fig. 11), but further research is required to more accurately investigate these relationships.

Few studies have been conducted on sustainable pasture management in temperate ecosystems. This is perhaps the first study on cattle management systems in temperate forest ecosystems. Future studies should quantify vegetation and soil microbes to determine mechanisms by which plant residues are broken down into soil carbon. The types of vegetation and microbes present may also change between pasture sites in response to either management or inherent qualities of the landscape. Soil nitrogen should also be quantified. Nitrogen directly correlates with carbon in the soil, such that a
greater N input results in greater carbon sequestration potential to a certain threshold (Parsons et al. 2013). Soil loss through erosion could also be quantified with the Revised Universal Soil Loss Equation (RUSLE; Wischmeier & Smith 1978). This would provide information about how and where soil is being lost through erosion and amendments could be made to prevent further loss.

![Figure 11](image.png)

Figure 11. Differences in percent clay and percent soil organic matter (SOM) between pasture and forest soil in a non-rotational (NR) pasture. A significant difference in SOM ($p < 0.001$) was observed between pasture and forest, but no difference was found with respect to clay ($p = 0.12$).
Conclusion

Oxidation and erosion of soil organic matter emits 61 billion tons of carbon into the atmosphere per year, compared to the 4 billion tons emitted from the burning of fossil fuels and 2 billion tons from deforestation (FAO 2006). Cattle are a major contributor to this equation. Overgrazing results in soil erosion, releasing stored soil carbon into the atmosphere (Da Silva et al. 2014; Wu & Tiessen 2002). The reduction of aboveground biomass associated with overgrazing increases the risk of erosion by both wind and rain due to loss of root structure and soil surface protection (Koiter et al. 2017). Additionally, in areas of overgrazing, soil becomes more trampled and compact, limiting water infiltration (Hamza & Anderson 2005). While carbon can be held long-term within the soil, erosion releases carbon dioxide into the atmosphere, perpetuating climate change.

There are, however, changes that can be implemented to help reduce cattle pasture contributions to climate change. The rotation of cattle about a pasture has been shown to increase soil carbon in tropical (Abril & Butcher 2001; Mazzetto et al. 2015), prairie (Teague et al. 2011; Wang et al. 2015), and arid regions (Chen et al. 2012; Han et al. 2008; Pei et al. 2008), but there is limited research on the effects in temperate regions. As temperatures and precipitation continue to increase, a transition from cropland to pastureland is expected, and this change is anticipated to be more pronounced in the temperate southeastern United States (Mu et al. 2012). Therefore, sustainable management of pastures and soil carbon will have a large role to play in mitigating climate change.

In addition to benefitting the environment, rotating cattle is valuable to the farmer. Although it may be too costly and time-consuming for most farmers to rotate their cattle
daily, some form of rotation will improve SOM. Although the HFR pasture had the greatest content of SOM, the LFR pasture had significantly more SOM compared to the NR pasture. Both rotational pastures also had similar contents of SOM compared to their adjacent forests. However, the NR pasture showed considerable depletion of SOM compared to its adjacent forest. With greater SOM, plant growth is improved by providing soil nutrients, increasing water-holding capacity, and improving soil fertility. A greater food supply would then be available to cattle, and reliance on external food sources, such as corn, would decrease. With greater soil carbon, productivity, resilience, and sustainability of pastures are improved (Meyer et al. 2015; Rutledge et al. 2015).

This study suggests that by increasing the frequency of cattle rotation, more carbon can be sequestered within the soil. SOM was found to be greatest in the high-frequency rotational (HFR) pasture, followed by the low-frequency rotational (LFR) pasture, and the non-rotational (NR) pasture. The inverse was true for bulk density. Soil texture was found to differ between pastures, and of particular interest were the differences in percent clay. A positive correlation was observed for SOM and clay, as clay particles are lost through wind or rain erosion in degraded pastures.

To benefit both the environment and the farmer, intentional steps must be conducted to prevent overgrazing. Overgrazing allows for the loss of soil carbon through erosion as the result of inadequate root structure, aboveground biomass, and soil moisture. Rotational cattle management, in some frequency, could help to improve SOM content and reduce atmospheric carbon dioxide as a potential pathway to mitigate climate change.
V. References


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role of ruminants in reducing agriculture’s carbon footprint in North America.


